Raman scattering in quantum disks: enhanced efficiency of the electron-phonon interaction due to non-adiabaticity

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Recent experiments on Raman scattering in self-assembled $Ga_xIn_{1-x}As$ disk-shaped quantum dots [1] and in self-assembled InAs/GaAs quantum dots [2] have demonstrated a rich structure of peaks provided by the optical-phonon-assisted quantum transitions.

In the present work, we treat resonant Raman scattering via the multiphonon exciton transitions in cylindrical quantum dots, which are a model for self-assembled quantum dots studied experimentally in Ref. [1]. Within our model, we take a parabolic confinement in the lateral direction and a rectangular interface-barrier confinement in the axial direction. Exciton states in a quantum dot are determined by a variational method for a wide range of the lateral-confinement frequency parameter from the weak-confinement regime to the strong-confinement regime.

Optical-phonon modes and the Hamiltonian of the electron-phonon interaction are considered within the multimode dielectric model [3, 4]. The model exploits both electrostatic and mechanical boundary conditions for the relative ionic displacement vector, as well as the phonon spatial dispersion in bulk, and explicitly takes into account the fact that the number of phonon degrees of freedom in the quantum dot is finite. We show that the confined phonon modes in a quantum dot are hybrids of bulk-like and interface vibrations.

We interpret the experiments [1, 2] taking into account the effects of *non-adiabaticity*, which have been shown in Ref. [5] to play a crucial role in the optical spectra of quantum dots. The interaction of an exciton in a degenerate state with phonons results in the internal non-adiabaticity (the proper *Jahn-Teller effect*), while the existence of exciton levels separated from each other by an energy, which is comparable with the optical phonon energy, leads to the external non-adiabaticity (the so-called *pseudo-Jahn-Teller effect*). We demonstrate that, due to the non-adiabaticity of the exciton-phonon system in quantum dots, different additional channels of the phonon-assisted optical transitions open.

Oscillator strengths of phonon modes in Raman spectra are investigated as a function of the confinement frequency parameter. For hybrid phonon modes, confined to a quantum dot, and for interface phonon modes, the values of oscillator strengths increase with increasing the confinement frequency parameter (see Fig. 1). Consequently, multiphonon peaks in Raman spectra can be observable even in quantum dots with weakly polar semiconductors. The calculated values of the total oscillator strength are in agreement with those for recently measured one- and two-phonon sidebands in Raman spectra of self-assembled InAs/GaAs quantum dots [2]. The aforesaid behavior of the oscillator strengths as a function of the confinement parameter is a manifestation of the *enhanced efficiency* of the electron-phonon interaction in strongly confined systems. It is provided (i) by increasing spatial separation between electron and hole charge densities with strengthening confinement due to a finite interface potential barrier; (ii) by non-adiabatic transitions. This enhancement has been shown recently also in the theoretical study of the photoluminescence spectra of quantum dots [5, 6].

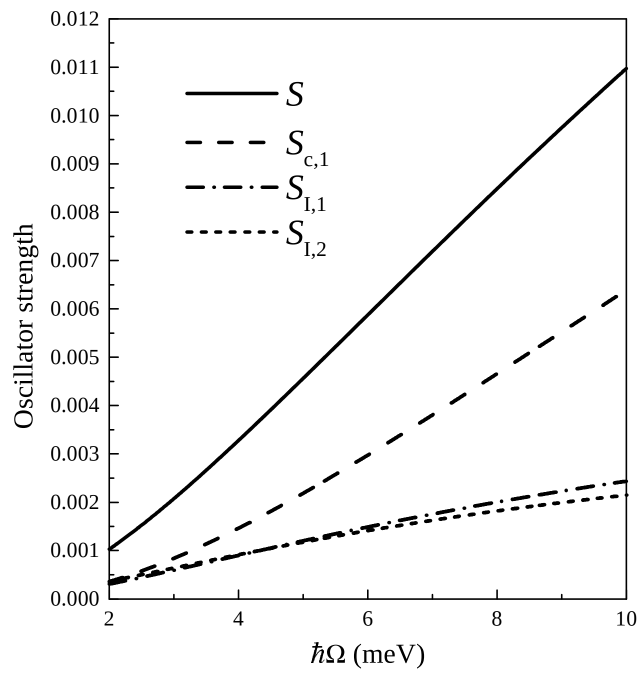

Fig. 1. Oscillator strengths of several phonon modes in a cylindrical GaAs/AlAs quantum dot with the height $h = 5$ nm as a function of the confinement frequency parameter Ω. $S_{c,1}$ is the oscillator strength for the most long-wavelength confined mode, $S_{I,1}$ and $S_{I,2}$ are those for GaAs-like and AlAs-like interface modes. S is the total oscillator strength (the Huang-Rhys parameter).

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